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ION ACCELERATION AT THE EARTH'S BOW SHOCK: A REVIEW OF OBSERVATIONS IN THE UPSTREAM REGION

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ABSTRACT

Positive ions are accelerated at or near the earth's bow shock and propagate into the upstream region. Two distinctly different populations of these ions, distinguished by their greatly different spectral and angular widths, can be identified there. The type of ion population observed in the upstream region is strongly correlated with the presence or absence of long-period compressive waves in the solar wind. Very few ions are accelerated in the vicinity of the shock to energies much above about 100 keV. It is not yet clear whether the most energetic ions (i.e. those near 100 keV) are accelerated at the shock or in the broad disturbed region upstream from the shock. In either case stochastic acceleration by turbulent electrostatic fields seems to be the most viable candidate for the acceleration of the most energetic particles.

INTRODUCTION

Collisionless shocks play a central role in several models of particle acceleration in astrophysical plasmas. Of the known astrophysical shocks, the detached bow shock standing in front of the earth's magnetosphere is the one most accessible to comprehensive and direct measurements. Although there have been surprisingly few published observations relating to particle acceleration at the bow shock, the observations available are considerably more detailed than can be obtained for other astrophysical shocks. Our intent here is to review those aspects of the observational literature which seem to be important for gaining an understanding of the mechanisms responsible for ion acceleration at or near the earth's bow shock.

The bow shock exists as a permanent feature of the interaction of the supersonic and superalfvenic flow of the solar wind past the earth's magnetosphere.[1] It serves to compress, heat, slow, and divert the solar wind around the magnetosphere. Because the solar wind ions are strongly heated within the shock, some of the particles in the post-shock flow (i.e. in the magnetosheath) have higher energies than in the flow upstream from the shock. Thus, whereas protons with energies exceeding 3 keV are uncommon in the typical solar wind where the average flow speed is 470 km s^{-1} and the temperature is 1.2×10^5 °K,[2] they are common within the magnetosheath where the temperature often exceeds 10^6 °K.[3] (See, for example Figures 5 and 9 of this paper.) The details of ion thermalization within the shock are not well established and apparently depend on such things as the interplanetary field orientation relative to the shock normal, the mach number of the flow, and the

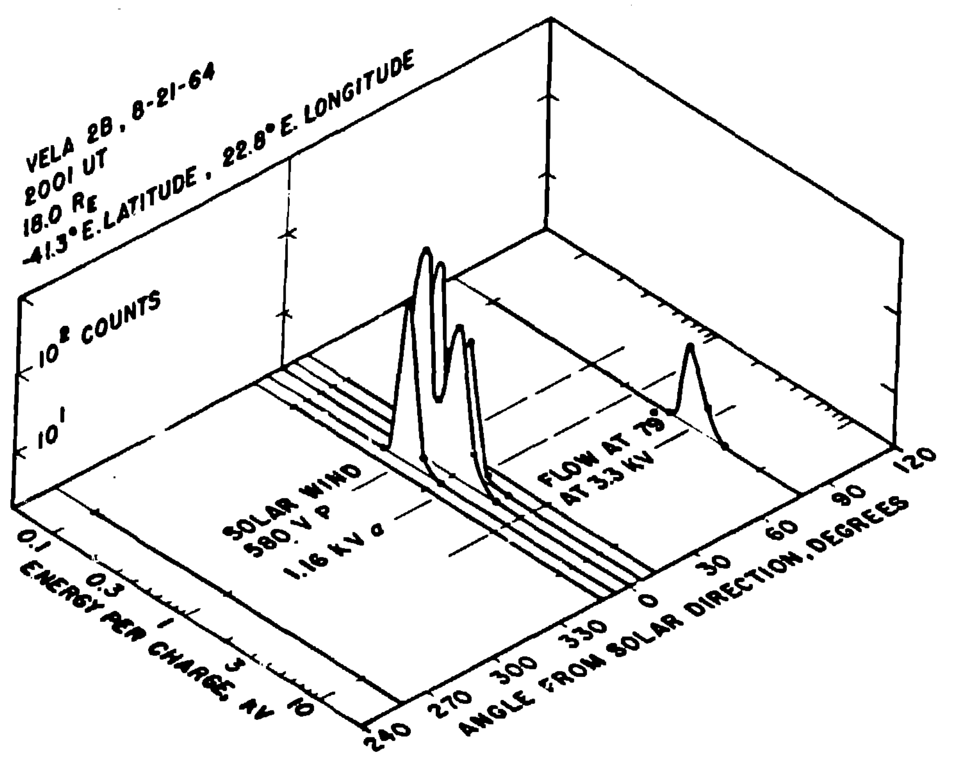

Fig. 1. Three-axis plot of ion measurements upstream from the earth's bow shock on 21 August 1964.[5]

ratio of electron to proton temperature in the upstream region.[4] However, it seems certain that thermalization is the result of particle scattering and acceleration by the electrostatic wave field which exists within the shock. We will not have more to say about ion thermalization at the shock since presumably this is not the type of acceleration process of most interest to this conference.

INITIAL OBSERVATIONS OF ION ACCELERATION AT THE SHOCK

Upstream from the earth's bow shock there exists a broad region rich in particle, field, and wave structure. This region is known as the foreshock[4], and owes its structure primarily to particles accelerated at or near the bow shock which propagate upstream. The first report of backstreaming ions in the foreshock region appeared in 1968[5] and Fig. 1 is taken from that work. Shown there is a 3-axis plot of detector counts versus energy and angle during an upstream ion event detected by Vela 2. The Vela 2 electrostatic analyzers performed energy sweeps at each of 7 different look angles. Five of these were clustered about the solar direction to monitor the solar wind flow. The double-peaked appearance of the solar wind spectra is caused in this case by the two major ionic constitutents of the solar wind - protons and alpha particles. Two additional energy sweeps were made approximately 80 and 100 degrees away from the solar direction. Ions with mean energy ~5.7 times the mean solar wind proton energy were detected on one of these sweeps. It happened that this look direction corresponded roughly to the nominal connection of the satellite to the bow shock via the interplanetary magnetic field. It was suggested that these ions were solar wind ions which had been reflected and accelerated at the shock and were traveling upstream into the solar wind along the interplanetary magnetic field. We now know that ion reflection is a common property of both laboratory[6] and astrophysical collisionless shocks. In 1969 Sonnerup[7] suggested that the solar wind ions are accelerated when reflected because they are displaced in the direction of the interplanetary electric field (the $\overline{V} \times \overline{B}$ field) while undergoing reflection. Energy gains of the order of 4-6 keV were predicted by this model, as was observed. To our knowledge, Sonnerup's model remains the favored one for the observed ion acceleration. However, later in this review other possibilities are discussed.

The original observations of backstreaming ions indicated that the reflected ions were a more or less permanent feature of the foreshock region, particularly on the dawn side of the magnetosphere where the magnetic connection to the shock is most favorable owing to the spiral nature of the interplanetary magnetic field. Preliminary calculations suggested that at times perhaps 10% of the ions incident on the shock and 40% of the energy were reflected back upstream. We now know these early estimates to be incorrect. Recent measurements with instruments specifically designed to study the reflected component indicate that typically ~1% of the ions incident on the shock and ~6% of the energy are reflected upstream.[8]

LONG-PERIOD MAGNETIC WAVES IN THE FORESHOCK REGION

About the time the upstream ions were first being discovered, several experimental groups reported the observation of long period (10-60 seconds in the spacecraft frame) magnetic waves in the foreshock region.[9,10] Figure 2 illustrates the appearance of these waves on interplanetary magnetograms. Shown here are temporal variations in the X, Y, Z components (solar ecliptic coordinates) of the interplanetary magnetic field sampled every 2.6 seconds during an upstream wave event. The experimental groups suggested that these waves were generated by a two-stream instability between the backstreaming ions and the solar wind bulk flow. In 1970 Barnes[11] constructed a theory for this process, and Scarf and colleagues[12] showed several events where the backstreaming ions and the upstream waves were observed simultaneously, indicating that the ions were indeed in some way responsible for the production of the waves. Another possibly crucial observation reported by Scarf et al. was that electrostatic turbulence with amplitudes of the order of 1 millivolt per meter accompanied the upstream waves; in particular, the electrostatic turbulence was strongest where the field gradients within the waves were largest. We shall return later in this review

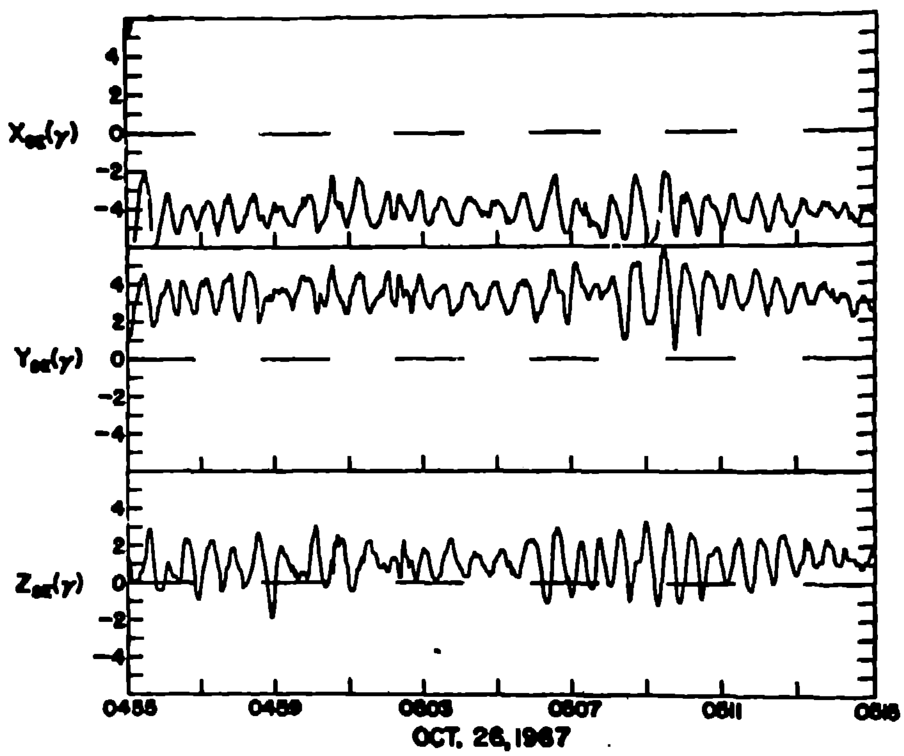

Fig. 2. Three components of the interplanetary magnetic field for a 20-minute interval when long-period waves are present. This data was obtained in the foreshock region.[10]

to the association of the waves with the upstream ions, but now let us proceed to further observations of the ions themselves.

OBSERVATIONS OF MORE ENERGETIC IONS

In 1974 Lin, Meng, and Anderson[13] extended the upstream ion observations to higher energies. Figure 3 is taken from their work and shows time histories of ions observed in the upstream region in several energy bands from 29 to 360 keV. The rapid turning on and off of the particle fluxes was ascribed to rapid changes in the direction of the interplanetary magnetic field which alternately connected and disconnected the satellite to the bow shock. Lin et al. indicated that the upstream ions with energies above 30 keV were always present whenever the interplanetary magnetic field connected the spacecraft to the bow shock. (More recent measurements suggest that this is not the case.) Representative spectra of the >30 keV upstream ions are shown in Figure 4. A rather remarkable and consistent feature of these and similar spectra obtained at other times is the sharp cutoff at particle energies near 100 keV. In fact, the spectra are consistent with no particles being observed above ~100 keV when pulse pileup is taken into account.[13]

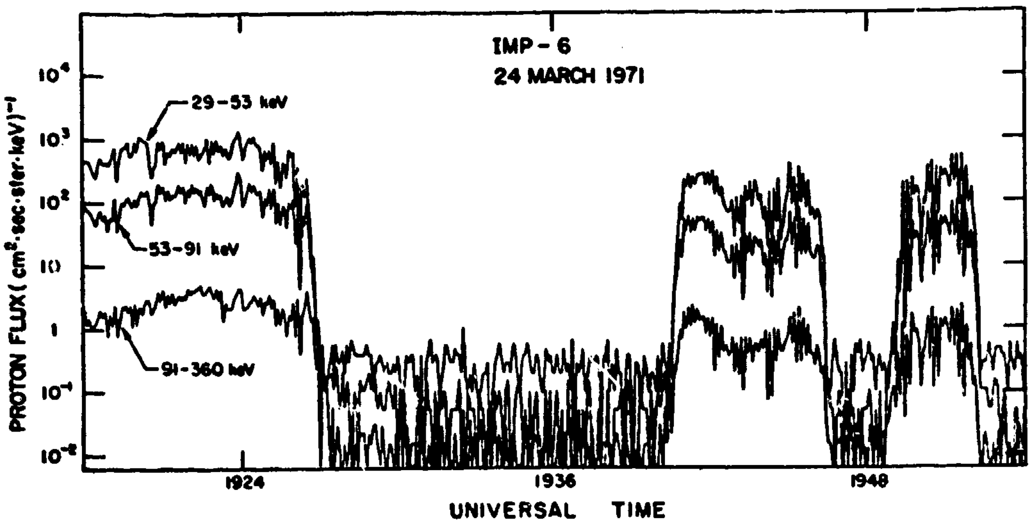

Fig. 3. Ion fluxes above 29 keV as a function of time in the foreshock region.13

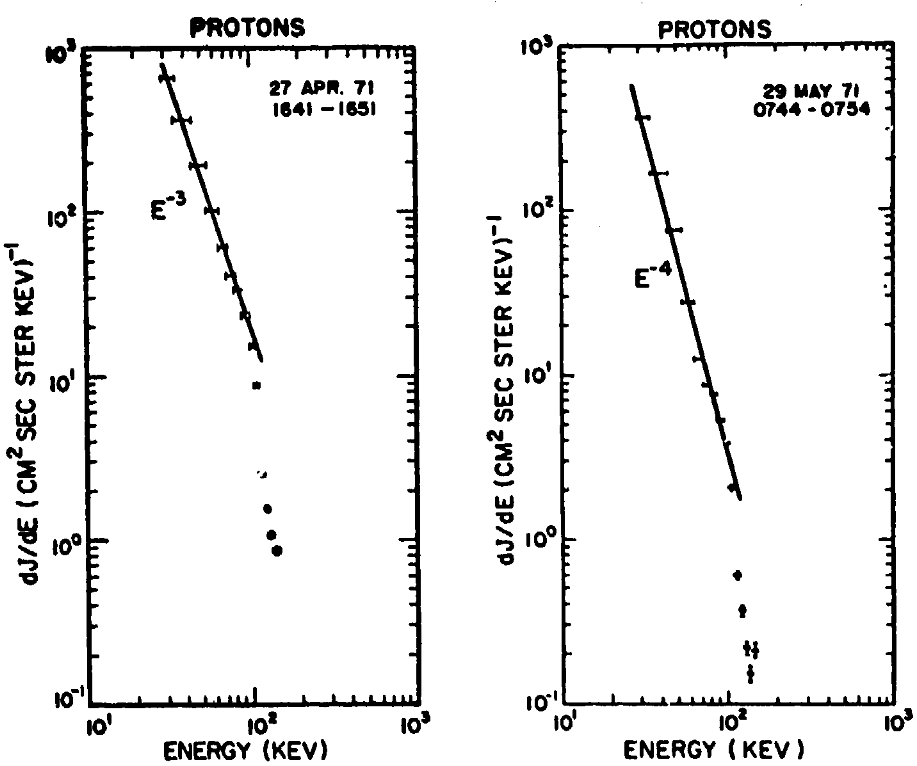

Fig. 4. Sample energy spectra of the upstream ions. The spectra are roughly power law from 30 to 100 keV, and are sharply cutoff above 100 keV.13

For several reasons Lin et al. did not believe that the particles they were observing were accelerated at the shock itself. Foremost among these reasons were the following.

1) Velocity dispersion was not observed. Rather, particles of all energies arrived at the spacecraft at the same time. Assuming that some disturbance emanating from the shock was responsible for the particles, Lin et al. found that the arrival time at the spacecraft was consistent with a propagation speed of $\sim$2.5 times the bulk speed of the solar wind, corresponding to a particle energy of $\sim$6 keV.
2) There was remarkably little attenuation of particle intensity with increasing distance from the shock.

As a result, Lin et al. suggested that the 30-100 keV ions were accelerated throughout the foreshock region on field lines which connected to the shock. Although they did not suggest a specific mechanism, they did indicate their belief that the lower energy ions ($\sim$6 keV) reflected and accelerated at the shock together with the long period magnetic waves were in some way responsible for the origin of the 30-100 keV particles. This idea was not universally accepted, however. For example, another suggestion was that the 30-100 keV ions were produced at the shock by multiple encounters with the shock as the reflected particles attempted to spiral away from it.[14]

RECENT OBSERVATIONS

In October 1977 the ISEE 1 and 2 satellites were launched into far-earth orbit carrying several instruments which were designed for studies of the upstream ion particles. One of the instruments aboard both ISEE 1 and 2 is the joint Los Alamos/Max-Planck Garching fast plasma experiment which scans all spacecraft longitudes with an ion energy range extending from 35 volts to 39.4 keV.[15] A spectrogram of the data from the instrument on ISEE 1 for the 1800-2400 UT interval on 19 November 1977 is shown in Fig. 5. At the beginning of this interval the satellite was at $\sim$18 R_E and 320° longitude and moving inward towards the dawn side of the shock. The upper 4 panels display ion energy spectra averaged over longitude for the angular quadrants centered respectively on the noon, dusk, midnight, and dawn meridians. The fifth panel displays ion angular distributions summed over all energies. Time runs from left to right on the spectrogram, with 6 hours of data being displayed. Intensity is proportional to the measured count rate. The relatively intense and narrow ion beam in the first and fifth panels is the incident solar wind. Encounters with the bow shock occur at ~2050, 2100, 2145, 2205, and 2220 UT, the magnetosheath (or post-shock flow) being identified by the greatly broadened energy spectra and angular distributions at those times. Upstream ions are present beginning about 1830 UT and continuing until the final shock crossing near 2220 UT. Two distinct populations are apparent in the spectrogram. For reasons which should become apparent we call these 2 types "reflected" and "diffuse" upstream ions.[8] Reflected upstream ions are distinguished by their narrow spectral and angular

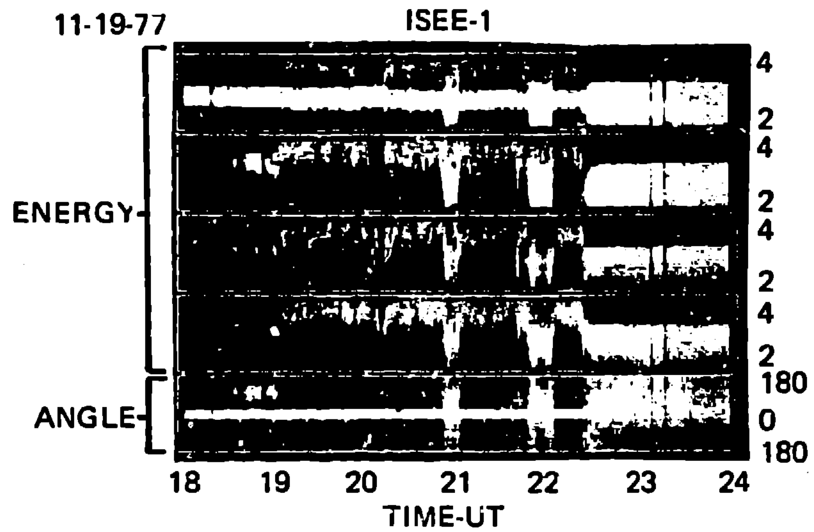

Fig. 5. A plasma spectrogram obtained on 19 November 1977 illustrating the two distinct and mutually exclusive populations of upstream ions. See text for details.[8]

extent, i.e. they are a beam of particles moving upstream along the interplanetary magnetic field. The upstream ions from ~1830 to ~1900 UT are of this type. On the other hand, diffuse upstream ions are characterized by relatively flat energy spectra extending upward to the highest energies sampled and broad angular distributions. Usually the diffuse ions have lower peak intensities than the reflected ions, but, importantly, comparable numbers of particles are generally contained within each type of upstream ion event. Ions of the diffuse type are present from about 1900 UT until the final shock crossing at ~2220 UT. Energetic ions similar to the diffuse upstream ion population are frequently observed within the magnetosheath.[16] On many occasions the diffuse ions and energetic sheath ions appear to be continuations of one another right across the shock as in the examples near 2100 and 2200 UT. On the other hand, there are also many examples in the data such as at 2220 UT where either the energetic sheath ions or the diffuse upstream ions end abruptly at the shock.

Representative samples of the measured angle integrated distribution function, f(v), of the reflected and diffuse ions on 19 November 1977 are shown in Fig. 6. In constructing f(v) it has been assumed that all of the ions are protons. The 2-count level shown is roughly equivalent to the background noise level of the instrument. As indicated by the arrow near the bottom of the figure the solar wind speed at the time of these measurements was ~395 km s^{-1}. The large differences between the spectra of the 2 types of upstream ions are readily apparent. Note that the lower energy cutoff for both populations is close to the energy of the solar wind flow.

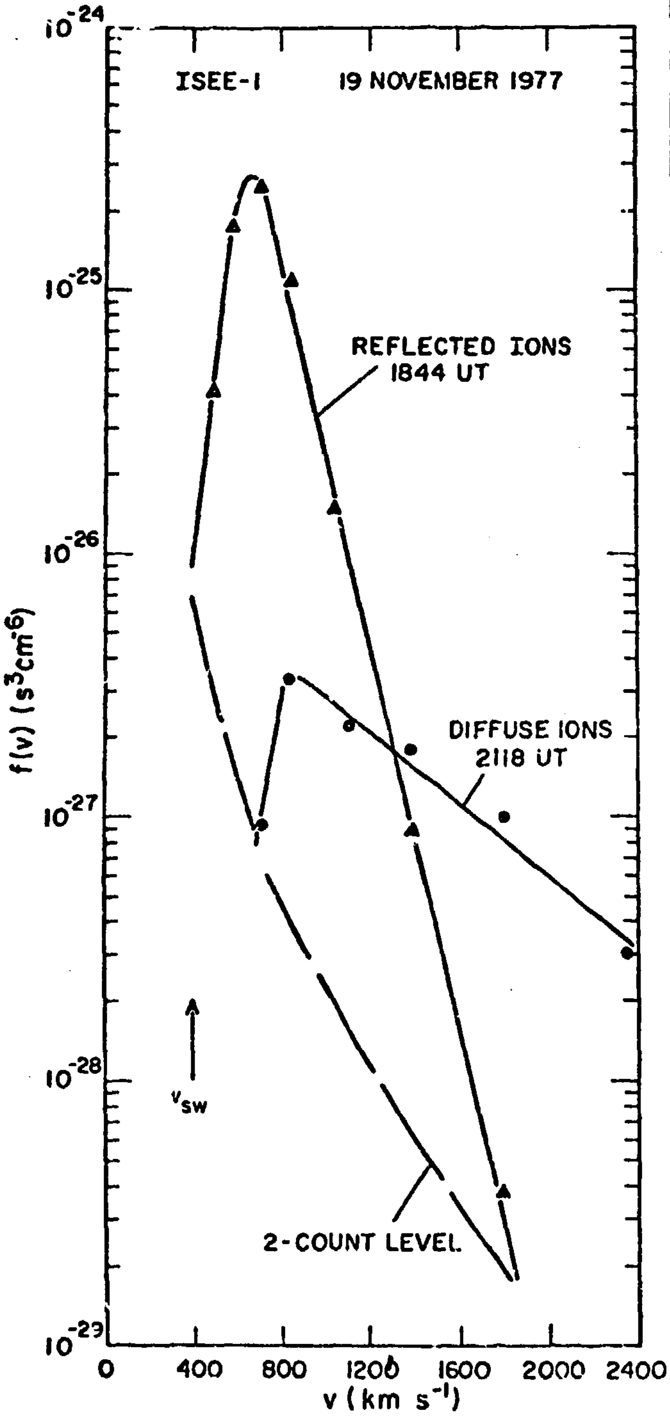

Fig. 6. Representative samples of the measured distribution functions of the two upstream ion populations on 19 November 1977.[8]

An examination of the first few months of the ISEE 1 and 2 data has established that the 19 November 1977 sample of data shown in Figs. 5 and 6 is representative. Throughout the foreshock region two different populations of upstream ions can be identified, and these two populations seldom, if ever, coexist. The "reflected" ions generally come from the direction of the bow shock along the magnetic field and have sharply peaked spectra generally extending from about 1 to about 10 keV. These ions often come in bursts sometimes as short as 1 or 2 minutes in duration and seldom lasting longer than an hour. "Diffuse" upstream ions on the other hand are distinguished by their relatively flat energy spectra usually extending at least as high as 40 keV (but peaking near 4 keV) and by their more iostropic angular distributions. Although at times bursty in appearance, more typically the diffuse ion events endure for hours at a time. Consequently, the diffuse ions are by far the more common of the two types of upstream ions observed. It is highly probable that the 30-100 keV ions discussed by Lin et al. are merely the high energy tail of the diffuse ion population. Note that since f(v) peaks near 4 keV, most of these ions have energies considerably less than 30 keV. (There is, however, a flux discrepancy between the Lin et al. measurements as shown in Fig. 4 and the spectra shown in Fig. 6. It is a straight forward matter to show that the conversion factor between Figs. 6 and 4 is 9.58×10^{14} v^2, where v is the speed in cm s^{-1}. Thus for 19 November the differential flux at 30 keV is 1.58×10^4/cm^2 sec str keV. This is approximately a factor 10 greater than the values reported by Lin et al. and also approximately a factor of 10 greater than values quoted by Ipavich et al.[17] and shown in Fig. 11. The origin of this discrepancy is at present unknown.)

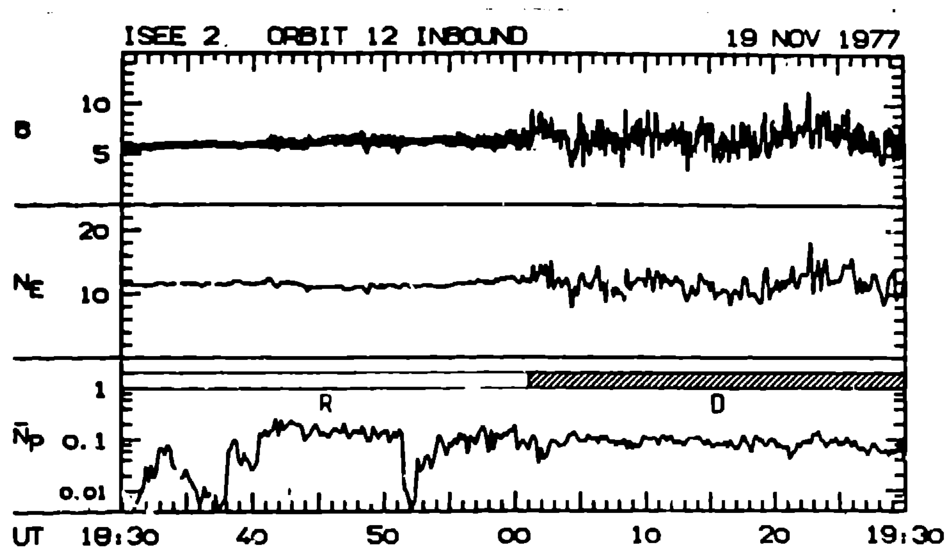

Fig. 7 Magnetic field strength, solar wind electron, and upstream ion densities on 19 November 1977. Spacing of the plasma measurements is 12 seconds. The bars in the 3rd panel identify the type of upstream ion event.[18]

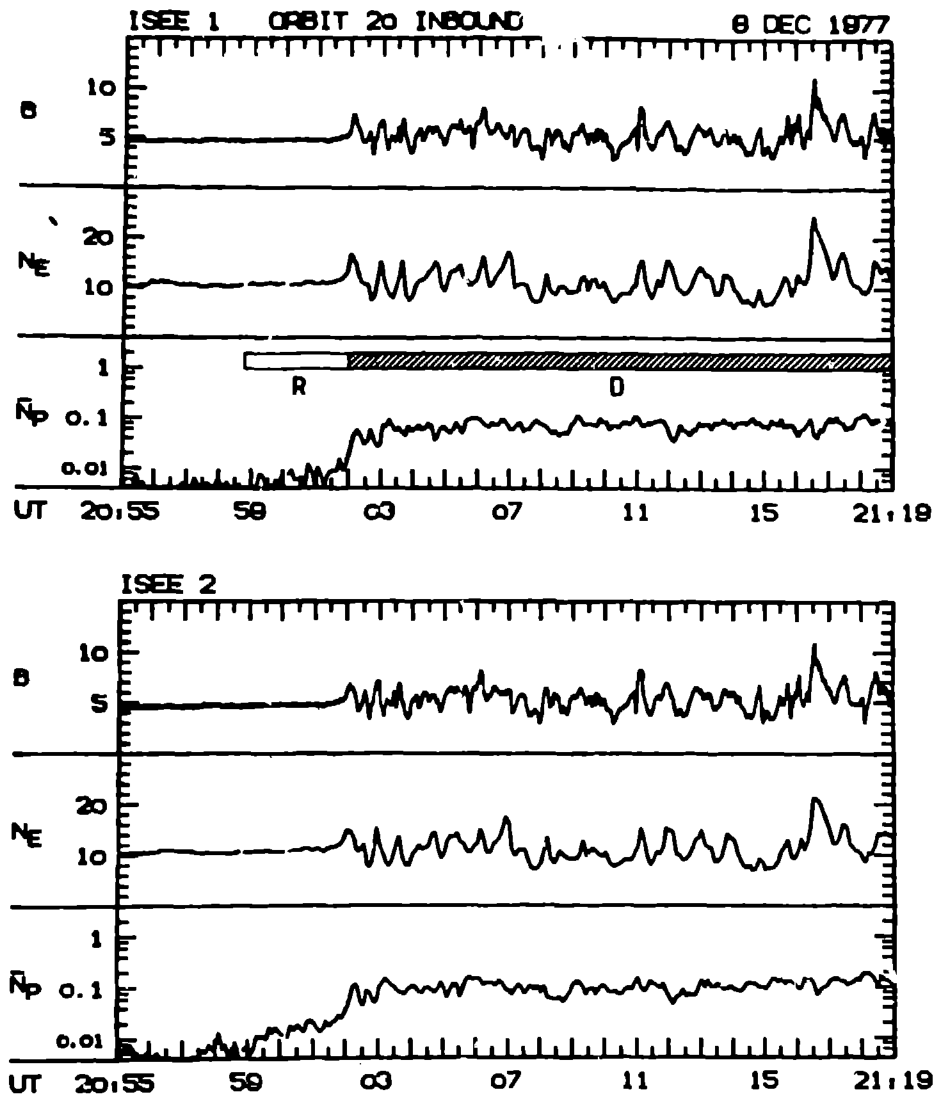

Fig. 8. Magnetic field strength, solar wind electron and upstream ion densities on 8 December 1977 as observed by ISEE 1 (upper panels) and ISEE 2 (lower panels). Spacing of the plasma measurements is 3 seconds, whereas the field is sampled every 24 millisecs. The bars in the 3rd panel identify the type of upstream ion event.[18]

A rather striking correlation exists between the diffuse population of upstream ions observed and the long-period magnetic waves previously discussed[18] (see Fig. 2). A 1-hour segment of ISEE-2 data obtained during the 19 November 1977 upstream ion events is shown in Fig. 7. The magnetic field data is from the UCLA magnetometer aboard ISEE 2 and is shown in the upper panel. The solar wind electron density, N_e, is shown in the second panel, and the density of upstream ions, $\overline{N}_p$, is shown in the bottom panel. Bars above the $\overline{N}_p$ plot indicate the type of upstream ion event. Note that the change from reflected to diffuse populations at ~1901 UT coincides with the onset of large amplitude fluctuations in B and N_e with a period near 30 seconds. Further, comparable numbers of upstream ions are present throughout this 1-hour interval, indicating that it is not the number of upstream ions that are important for the wave correlation but rather the way the ions are distributed.

A further example of the correlation between upstream ion population type and the long-period waves in the solar wind is shown in Fig. 8. The format is the same as in the previous example except that simultaneous data from each of the closely spaced ISEE satellites are displayed and the time scale has been expanded. A brief weak burst of reflected ions occurred from ~2055 until ~2102 UT, and was followed by a long lasting diffuse ion event. Important aspects of this figure are emphasized below.

1) The onset of large amplitude fluctuations in B and N_e is sudden at both spacecraft and coincides with the appearance at the satellites of diffuse upstream ions.
2) The reflected ions again have no noticeable effect upon B or N_e.
3) Wave amplitudes are high, the fluctuations in both B and N_e being comparable to the average values.
4) There is excellent coherence between the oscillations in solar wind electron density and field strength at both satellites, indicating that the waves are compressive.

We have stressed that there are basically two distinct populations of upstream ions which do not coexist. However, Figure 9 illustrates that it is not always easy to distinguish between the two populations. Shown here is an ISEE 1 spectrogram obtained on 8

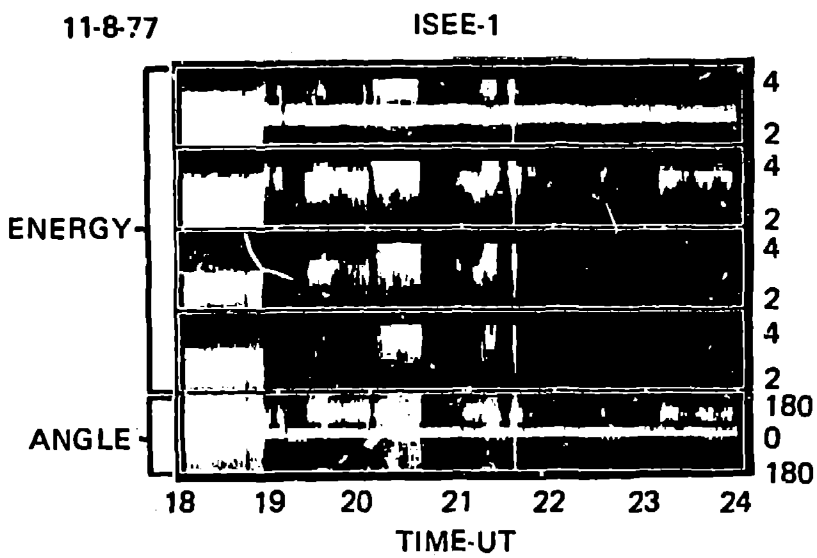

Fig. 9. A plasma spectrogram obtained on 8 November 1977. See text for details.[8]

November 1977. The format is the same as Fig. 5. A bow shock crossing from the magnetosheath to the solar wind occurred at ~1853 UT. Although the short bursts of upstream ions near 1855, 1900, 2100, 2145, and 2230 UT and the long burst after 2310 UT are clearly the reflected population, and the bursts from ~2005-2030 UT and from 2110-2120 UT are clearly the diffuse population, the long burst from ~1920-2000 UT seems midway between. It has a broader spectral and angular extent than is typical of the reflected population, but is still more highly beamed and restricted in energy than is typical of the diffuse population. Figure 10 shows three 1-hour segments of the solar wind data on 8 November in a format similar to Figs. 7 and 8. The previously noted absence of waves in conjunction with the reflected ions is clearly evident during the bursts near 1855 and 1905 UT and during the long interval between ~2310 and 2357 UT. In constrast, large amplitude waves are seen between ~2002 and 2034 UT when the diffuse ions are present. But perhaps the most interesting feature of this figure is the small amplitude (yet significant) fluctuations in B and N_e from ~1920-2000 UT when ions of an intermediate nature were observed.

Various studies of the occurrence of upstream waves, primarily by Greenstadt and colleagues,[4] indicate that the long-period waves we have been discussing are correlated with the angle the interplanetary magnetic field makes to the local shock normal. In particular, they find the waves generally are present when this angle is less than 45° and generally absent when this angle is greater than 45°. It has been stressed that 45° corresponds roughly to the division between quasi-perpendicular shock structure (where the shock transition is well-defined and has a thickness of ~100 km) and quasi-parallel shock structure (where the shock does not appear as a discontinuity in the true sense of the word).[19,20] This suggests that the upstream waves (and thus also the diffuse upstream ions) may be an integral part of the quasi-parallel shock structure. We have not performed a general investigation of the relationship between upstream ion populations and the orientation of the interplanetary magnetic field relative to the shock normal. However, for the 8 November 1977 example we find[18] the angle between the field and the local shock normal was 58° or greater when no upstream ions were present. It averaged ~50° when reflected particles were present, ~40° when intermediate ions were present, and ~30° when the diffuse ions were present. These values are roughly consistent with the earlier wave results.

Up to this point we have tacitly assumed that all of the upstream ions are protons. However, with the joint University of Maryland/Max-Planck Garching experiment on ISEE 1 it is possible to distinguish the various ionic species present in these events.[17] Figure 11 shows typical spectral data from this experiment for a diffuse upstream ion event on 31 October 1977 which illustrates that alpha particles and heavier elements are also present. In fact, as might be expected, these groups find that the elemental abundance of the upstream ion events is similar to that normally present in the

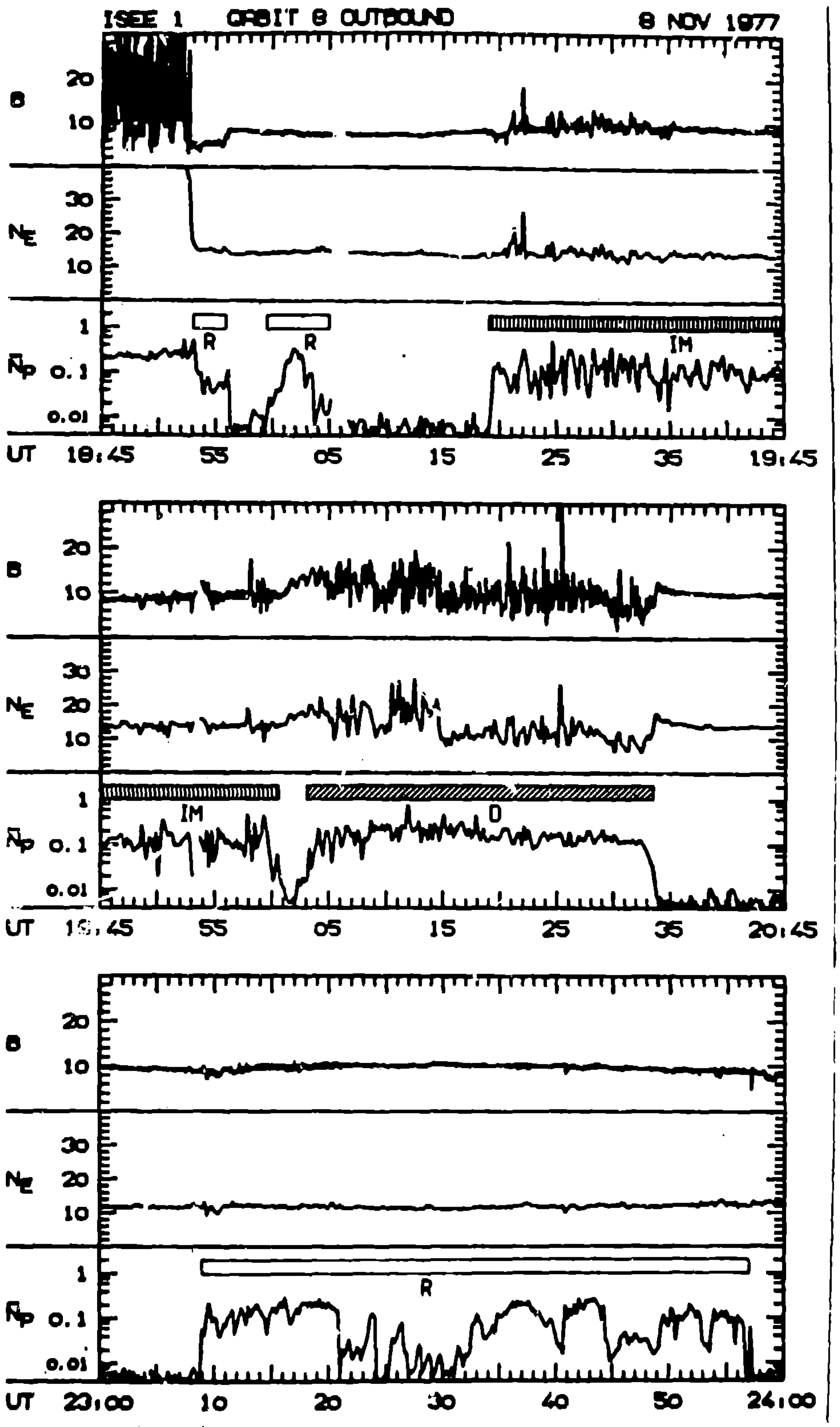

Fig. 10. Magnetic field strength, solar wind electron density and upstream ion densities for 3 1-hour intervals on 8 November 1977. The bars in the 3rd panel of each set identify the type of upstream ion event.[18]

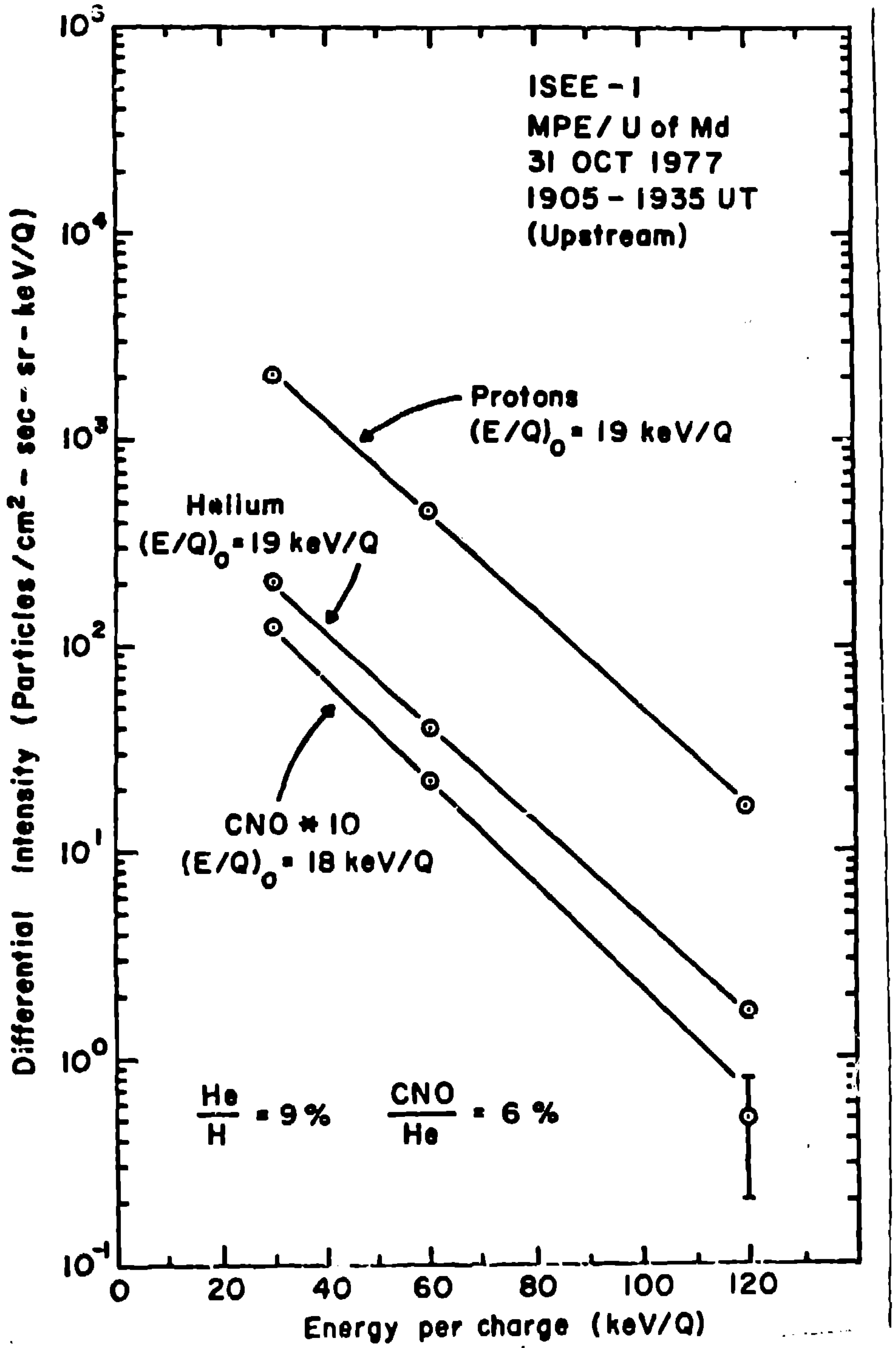

Fig. 11. Energy spectra for various elements during a diffuse upstream ion event on 31 October 1977.[17]

solar wind. Ipavich et al. also emphasize that their data are best organized in terms of energy per charge (E/q). For example, the composition is nearly constant at all values of E/q. This clearly suggests the upstream ions are accelerated by electric fields.

Finally, in summarizing the observations of ions associated with the bow shock, mention should be made of the much more energetic ions (~100 keV-1 MeV) which have been observed in the foreshock region. Several groups[21,22,23] have reported the rather common occurrence of such ions in the upstream region. Although originally it was thought that these more energetic ions were the high energy tail of the 30-100 keV protons discussed by Lin et al.[21] (i.e. the high energy tail of the diffuse population), it has recently become clear, as Fig. 12 illustrates, that these more energetic ions are a

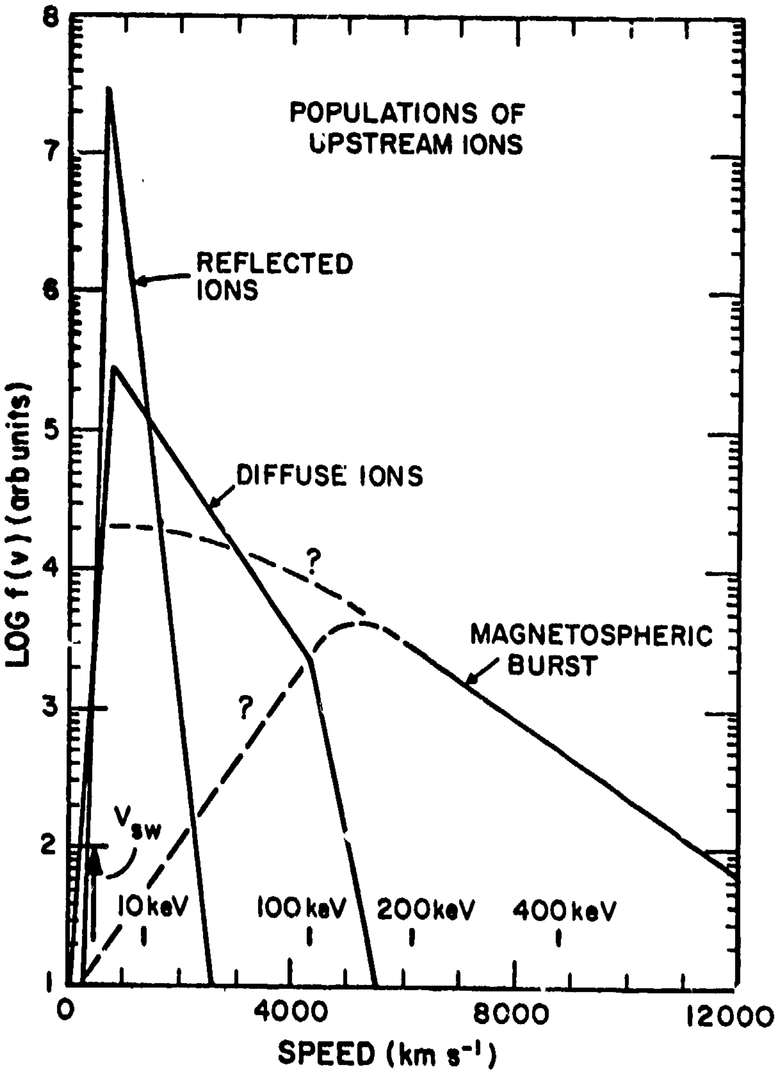

Fig. 12. Qualitative samples of the distribution functions of the 3 populations of energetic ions observed in the upstream region. Only the reflected and diffuse populations are thought to originate at or near the bow shock.

separate population which most likely originates in the earth's magnetotail. Briefly, the reasons for believing these ions have nothing to do with the bow shock are as follows.

1) They have a harder spectrum than either the reflected or diffuse ions.
2) They are observed simultaneously within the magnetotail, the magnetosheath, and the foreshock region, with the flux intensities being several orders of magnitude greater within the magnetotail.[22,23]
3) The bow shock ions (diffuse population) have spectra which drop sharply at ~100 keV.[13]

DISCUSSION

In the previous section an attempt was made to outline the important known characteristics of ions accelerated in the vicinity of the earth's bow shock and observed upstream. Extra emphasis has been given to the relationship of these ions to the long period waves also observed in the foreshock region because these waves may contribute to the acceleration of the more energetic particles in the events. It is important to note that most of the accelerated ions attain energies only several times greater than they had when incident on the bow shock. For the reflected population of ions, virtually no particles attain energies in excess of about 20 keV. For the diffuse population, less than 1% of the 1% of the ions which are accelerated attain energies as high as 100 keV. Further, virtually none of the ions accelerated in the vicinity of the bow shock attain energies significantly higher than 100 keV. By way of contrast, 1 MeV ions are commonly observed in association with corotating interplanetary shocks.[24,25,26] This discrepancy suggests either that different acceleration mechanisms or different initial particle populations are involved in the two cases, or that the field line geometry of interplanetary shocks (these shocks are generally highly oblique[27]) favors a greater net acceleration in that case.

We mentioned earlier that a model whereby ions are accelerated as they are reflected off the bow shock because they are displaced through a $\overline{v} \times \overline{B}$ electric field has gained rather broad acceptance. However, Tidman and Krall[28] and perhaps others have noted that the temperatures of the upstream ions seem to be too high to be explained by a simple reflection process. (It seems clear now that Tidman and Krall were discussing the diffuse population.) They therefore invoked a model of stochastic acceleration by electrostatic turbulence[29] in the shock. Figure 13 demonstrates that such turbulence certainly exists at the shock.[30,31] Shown there is the intensity of electrostatic noise for a typical bow shock crossing as observed at different frequencies. The lowest three panels show the magnetic field data in order to define the shock transition at ~2220 UT. Coincident with the shock crossing there is an enhancement in electrostatic noise. The amplitude of the noise (typically of the order of 1 millivolt/meter) is of the magnitude required by the model to produce the observed ion acceleration.

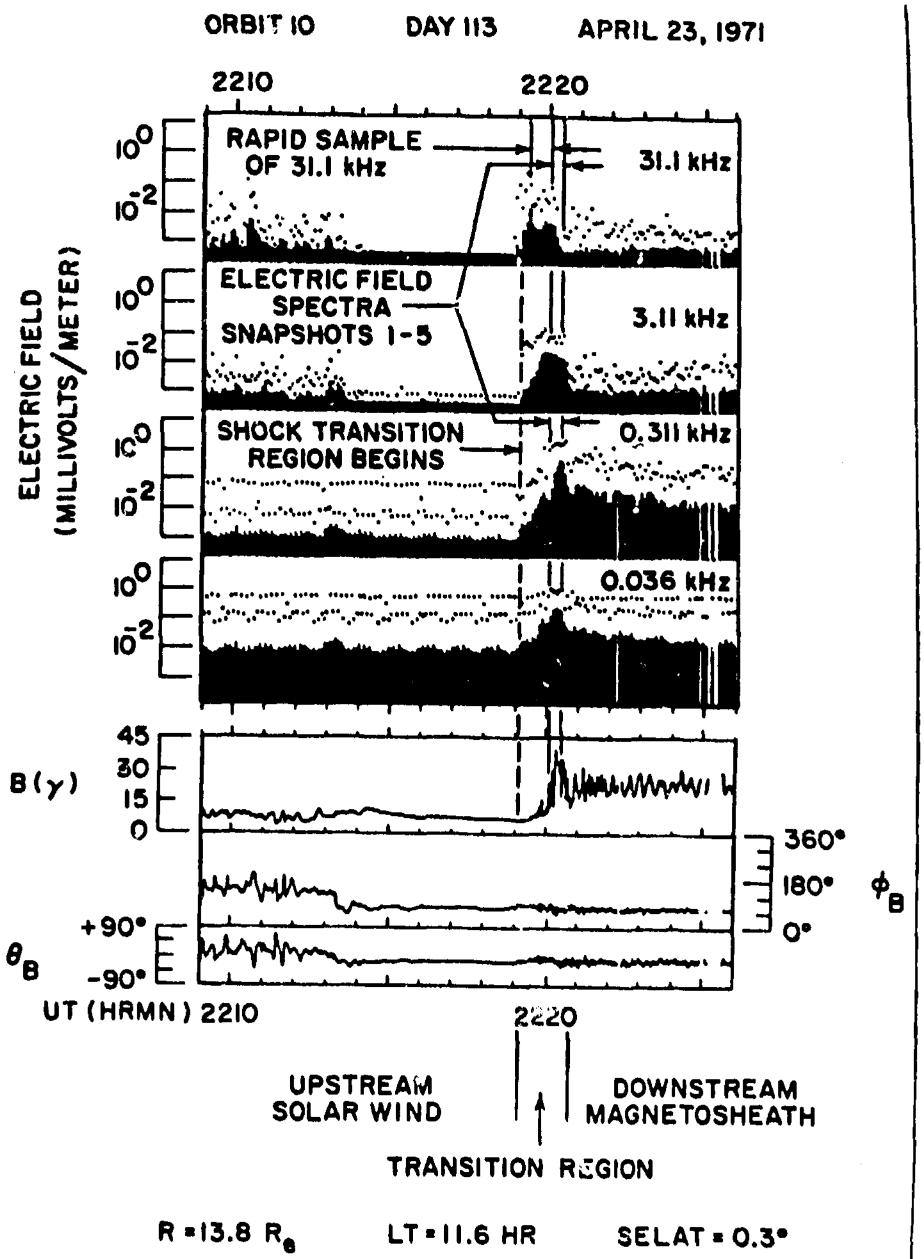

Fig. 13. A shock crossing which shows the relation between variations in electrostatic noise and the structure of the bow shock as observed by a magnetometer. Upstream electrostatic oscillations at 3.11 and 31.1 kHz are correlated with long-period waves in the magnetic field and hence also with diffuse upstream ions.[31]

Electrostatic noise of somewhat reduced amplitude is also observed in the foreshock region in connection with the long period magnetic waves.[12] An example of this can be seen in Fig. 13 in the 31.1 kHz and 3.11 kHz channels near 2210 UT. An important series of questions relative to this noise and the upstream waves might be posed as follows. Are the long-period waves and electrostatic noise the result of an instability driven by the reflected ions streaming upstream through the solar wind? If correct then the diffuse ion population is the result of scattering by the waves and stochastic acceleration by the electrostatic turbulence. Or, are the reflected ions stable and accelerated only under certain favorable interplanetary field configurations? And, are the diffuse ions produced at the shock by stochastic processes associated with a thickened shock transition when the shock is quasi-parllel? Are the upstream waves then generated only by the diffuse ions streaming through the solar wind?

Several of our observational facts fit the former hypothesis. For example, the fact that the two populations are not observed simultaneously yet contain approximately the same numbers of particles fits this picture well. So too does the correlation between wave amplitude and spectral and angular spread of the upstream ions. On the other hand the correlation of particle populations with the orientation of the field relative to the local shock normal and the observed long time stability (up to an hour) of the reflected component suggests that both populations may be produced at the shock under differing orientations of the interplanetary magnetic field. Hopefully, further analysis will help decide between these alternatives.

ACKNOWLEDGMENTS

Our original papers on ion acceleration at the bow shock using the ISEE 1 and 2 data were done primarily in collaboration with G. Paschmann and N. Sckopke. We have profited greatly from our continued interaction with them on these problems. We have also benefited from our interaction with C. Russell and G. Greenstadt on these problems. F. Ipavich and R. Lin kindly provided information from their ISEE 1 and 2 experiments prior to publication. This work was conducted under the auspices of the U.S. Department of Energy with NASA support under S-50864A.

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